

**TITLE OF THE INVENTION**

**HIGH VOLUME PRINT-FORMING SYSTEM**

### **CROSS-REFERENCE TO RELATED APPLICATIONS**

This application claims benefit under Title 35, United States Code §119(e) of United States Provisional Application No. 60/438,514 filed on January 8, 2003.

This application incorporates herein by reference the entire contents of U.S. Patent No. 5,348,693.

## **FIELD OF THE INVENTION**

The following invention relates to methods and apparatuses for manufacturing structures which can be defined as a series of stacked slices of a printable material. More particularly, this invention relates to high volume systems for print-forming structures by sequentially printing separate layers of the structures at multiple different locations simultaneously and then moving the partially formed structures to a new location for further printing until the structures have been completed.

## **BACKGROUND OF THE INVENTION**

The HVPF™ (High Volume Print-Forming) process of this invention is a new and unique manufacturing process with advantages in many applications and industries. This manufacturing process allows low cost production of small, complex structures or assemblies and co-fired ceramic circuits. A market exists for such structures with optimized designs not profitably manufacturable with current technologies that require the HVPF™ manufacturing process methods and devices. Included in these specialized devices presently described is the enabling support bed invention also referred to by the trademark “Ziggurat,” and associated substrate blocks also referred to by the trademark “Ziggys.” As will be described, the “Ziggurat” is a new species of a previously patented “Progressive Wedge” concept identified in U.S. Patent No. 5,348,693, incorporated herein by reference.

HVPF™ manufacturing processes are 3-D (three-dimensional) print-forming methods that can produce structures or assemblies from virtually any material that can be printed, bonded or sintered, including ceramic, glass, metal or polymer, and combinations of these materials, at high speed and low cost. It is not a rapid prototyping process and has few of the limitations of rapid prototyping. Structures can be produced from multiple materials and specific engineered parts can be designed into complex functional geometries including mechanical structures with moving parts and “preassembled” components built in-situ. HVPF™ enables the manufacture of complex geometric structures without increasing manufacturing costs and it provides freedom from many typical manufacturing constraints, allowing form to more closely follow function.

HVPF™ processes capitalize on advances in a number of technologies, including printing, ceramic and metal injection molding, CAD/CAM, advanced materials, robotics, sensors and imaging. The printing portion of HVPF™ process is similar to “two-dimensional” printing including screen printing, flexo, gravure or offset lithography. HVPF™ differs in that subsequent prints are layered on top of each other, like the pages

of a book, to print-form a three dimensional object, which is made entirely of the printed material. Different layers may contain different shapes, creating three-dimensional geometry when multiple layers are combined together, as shown in Figure 1. Further detail on the background of high volume print-forming by the known progressive wedge technique can be found by reference to U.S. Patent No. 5,348,693.

In its simplest form, the progressive wedge is physically a linear array of advancing unfinished structures, which are successively built from first to last, layer-by-layer, from the bottom-most layer upward. Only the last structure is complete as it receives the last layer. Every structure in the linear array receives the next layer on top of the previous layers at the same time as all the other structures, each structure getting the layer specifically required at its height at that time in the build sequence. With every cycle, the “oldest” structure comes off the end of the line finished, and one new structure is started at the beginning. The same printer image is printed every time, which consists of a linear array of cross section images of the structure. As noted before, there may be two or more materials used for each layer printed, and the structures only advance after all materials for that layer have been printed.

With structures that have many layers and relatively large dimensions, this progressive wedge and its associated printing machinery often would be, out of necessity, a proportionally long physical structure. The printer, with its repetitive print cycles, works with the progressive wedge as a printing platen, a means to reassemble a computer-generated structure that has been horizontally sliced into many thin, printable layers, into a real print-formed structure. As illustrated in Figure 2, the cyclical action of the screen would print all the different and successive layers onto the forming structures below, all at the same time, over and over again. Between every print cycle, the structures move along the progressive wedge one step left to right.

The “progressive” aspect of the progressive wedge refers to the fact that the structures being built move or “progress” one place between every printing cycle as

well as grow “progressively” in thickness with every printing cycle. Therefore, a structure starts out at one end of the progressive wedge by its first layer being printed onto a flat formation site. The partial structure then receives the second layer on top of the first and so on until it finishes at the other end with the last layer being printed on top of all the previous layers. This would be analogous to a waiter collecting plates, each of a different shape than the last, and stacking them on top of each other until there is a tall stack. The individual plates represent the print cycles; the stack represents the full structure.

The “wedge” aspect of the progressive wedge is specifically regarding the growing height of the individual structures as they move relative to the image being printed. The collective shape of the structures in progress forms a wedge in side view, with the thin end of the wedge at the beginning of the printing line and the thick end at the “finished structures” end. Being that the top surface of the wedge must remain level and parallel with the printing plane, the bottom surface of the structures must be progressively lowered one layer thickness at a time, as they advance. Using the plate analogy again, imagine the stack of plates in an automatic plate dispenser that keeps the top plate level with the serving table by adjusting the height of the bottom plate in the stack.

## SUMMARY OF THE INVENTION

The embodiment of the support bed or “Ziggurat” described herein is a species of HVPF™ based on screen-printing technology. For clarity, descriptions will be based on this technology, without excluding other printing methods usable with the machines, methods and apparatuses disclosed herein.

A screen printer machine pushes an ink with a squeegee-like device through a fine screen with an exact pattern of open spaces to create a layer of ink of the same pattern onto a flat surface just below the screen. The screen acts as a stencil or template for the ink. The “inks” used in this process include mixtures of ceramic and metal powders, polymers and binders, often in a paste form. These inks are used in particular combinations or alone to print structures that have specific materials incorporated exactly where they are needed in each structure.

Each layer of the structure being print-formed is preferably comprised of at least two materials when that layer is finished being printed. One material, or ink, is the material that makes up that particular cross-section of the structure being print-formed on that layer. This structure, on any given layer, may be composed of one or more materials, dependent on design, and these materials that compose the structure are called “positive inks.” Another material, called “negative ink” is typically printed around the cross-section of the structure itself on the same layer. This negative ink forms a temporary support around the positive ink. It is also referred to as “sacrificial material” as it is typically removed or sacrificed later to expose the final structure.

A different screen is used to print each of the different positive inks as well as the negative ink, as each has its specific shape to fill on that particular layer. The negative ink has several functions, including support of positive ink on the same layer, support of positive ink on the layer above and below, as the positive shapes often change on adjacent layers, and to maintain a level and complete printing surface on the whole area being printed, as shown in Figures 2 and 3.

What results in the system of this invention is a high volume print-forming arrangement including: a bed having a plurality of steps, at least two of the steps positioned at different heights relative to each other, a plurality of substrate blocks, each substrate block including a substantially planar upper surface and adapted to be positioned on one of the steps of the bed and to move between the steps while supporting upon the upper surface a structure being print formed, and a printer located above the upper surfaces of the substrate blocks and adapted to print material down toward the substrate blocks and upon the structures being print formed upon the substrate blocks.

After each printing step the substrate blocks move down one step and the printing process is repeated. Eventually, the layers being printed produce the completed structure. The negative material is then removed and the structure is complete or can be further treated as necessary.



## **OBJECTS OF THE INVENTION**

Accordingly, a primary object of the present invention is to provide a method for printing high volumes of identical structures by printing layers of the structure one layer at a time and shifting the partially completed structures between printing locations, before repeating the printing process to add further layers to the partially completed structures until fully completed structures result.

Another object of the present invention is to provide a method for rapidly manufacturing large numbers of identical structures, particularly structures having complex geometries.

Another object of the present invention is to provide an apparatus for manufacturing large numbers of structures by sequentially printing layers of the structures with material from which the structure is to be formed.

Another object of the present invention is to provide a high volume print-forming method and apparatus which has a relatively large number of distinct printing locations and which has printing locations arrayed in two dimensions to minimize an overall length of the region where the printing occurs.

Another object of the present invention is to provide a high volume print-forming method and apparatus which can precisely form high volumes of structures to exacting tolerances in a rapid low cost fashion.

Other further objects of the present invention will become apparent from a careful reading of the included drawing figures, the claims and detailed description of the invention.

## **BRIEF DESCRIPTION OF THE DRAWINGS**

Figure 1 is a perspective view illustrating the general concept of print-forming.

Figure 2 is a perspective view of a progressive wedge species of high volume print-forming.

Figure 3 is a perspective view of a completed structure such as would be formed by the high volume print-forming occurring as shown in Figure 2.

Figure 4 is a perspective view of the high volume print-forming system of this invention illustrating the position of the support bed and partially completed structures relative to a screen provided for print-forming the structures.

Figure 5 is a schematic illustrating how various components of this invention work together according to the method of this invention.

Figure 6 is a perspective view of a linear high volume print-forming method utilizing substrate blocks and screen printing technology according to this invention.

Figure 7 is a perspective view illustrating in general how a progressive wedge type of high volume print-forming is modified to provide high volume print-forming upon a support bed having lesser length.

Figure 8 is a perspective view illustrating how a screen can be used for screen printing on the high volume print-forming structure shown in Figure 7.

Figure 9 is a perspective view of a high volume print-forming system utilizing screen printing and simultaneously manufacturing parallel rows of structures.

Figure 10 is a perspective view of the support bed for use according to one form of this invention.

Figure 11 is a perspective view similar to that which is shown in Figure 10 but with substrate blocks shown resting upon the steps of the support bed according to one form of this invention.

Figure 12 is a perspective view of a lower surface of one of the substrate blocks shown in Figure 11.

Figure 13 is a schematic top plan view of a preferred shuffling pattern for substrate blocks upon the support bed according to this invention.

Figure 14 is a schematic representing the process of high volume print-forming according to this invention and further illustrating how starter substrate blocks are utilized along with regular substrate blocks to initiate the high volume print-forming process according to this invention.

Figures 15-18 are sequential schematic views further illustrating a preferred form of shuffling pattern according to this invention.

Figure 19 is a perspective view of a preferred form of shuffling machine according to this invention.

Figure 20 is a perspective view further illustrating details of the preferred shuffling machine of this invention.

Figure 21 is a schematic view of a first alternative shuffling pattern for moving the substrate blocks upon the support bed according to this invention.

Figure 22 is a perspective view of a portion of that which is shown in Figure 21 and illustrating how ribbons can be used to allow substrate blocks to effectively pass adjacent each other.

Figures 23-25 provide top plan views of portions of the first alternative shuffling pattern of Figure 21 and illustrating how substrate blocks can transition between rows at the end columns upon the support bed.

Figures 26-31 include perspective views and front elevation views of an alternative shuffling tool for moving the substrate blocks upon the support bed.

Figures 32-43 provide schematic views of a second alternative shuffling pattern for moving the substrate blocks upon the support bed.

Figures 44-46 are perspective views of various alternative shuffling patterns for moving the substrate blocks upon the support bed according to this invention.

Figure 47 is a perspective view of a substrate block holding tool for securely holding the substrate blocks in position upon the various steps of the support bed.

Figure 48 is a top plan view of one step of the support bed including a second alternative substrate block holding and alignment tool which includes vacuum to hold the substrate block adjacent the support bed.

Figure 49 is a full sectional view of that which is shown in Figure 48 and illustrating how a combination of vacuum and lift pins can be used for alternatively holding, aligning and lifting the substrate blocks before utilization of a shuffling tool to move the substrate blocks where desired upon the support bed.

Figures 50-53 reveal various alternative vacuum hole patterns for steps of the support bed.

Figure 54 is a perspective view of a magnetic holding tool to hold the substrate block upon the support bed.

Figure 55 is a perspective view of a mechanical holding tool for holding the substrate blocks upon the support bed.

Figure 56 is an underside perspective view of one of the substrate blocks and alignment pins in the support bed shown in section, taken along line 56-56 of Figure 57.

Figure 57 is a side view of the support bed shown in a section view taken along a line parallel with an alignment slot in the support bed.

Figures 58-60 show sequential schematic views of a second alternative shuffling tool for moving the substrate blocks upon the support bed.

## **DESCRIPTION OF THE PREFERRED EMBODIMENT**

Practically any shape that is computer modeled or is from a scanned source can be print-formed. The high volume print-forming HVPF™ process “slices” each complex shape into many sequential distinct cross-sections in a computer model. Each of these slices 34 (Figure 4) is the thickness of a printed layer. The system then prints all the different cross-sections of a structure at the same time in adjacent spaces. As a result, many identical structures are being built at once, but each structure is in its own stage of construction. For example, a shape might be sliced into ninety-six cross-sections. In this example (Figure 4), cross-sections one to ninety-six would be printed all at once but each cross-section would go into the correct location in ninety-six separate structures. With each cycle of the press screen 30, a completed structure 38 would come off the press, a new structure would be started, and all cross-sections from one to ninety-six would be printed again. In other words, with the technology, ninety-six structures are “works in progress” all at once, as shown in Figure 4.

Between printing cycles of printing station 40 (Figure 5), including the positive printer 42 and the negative printer 43, the ink layers are typically quickly cured at a cure station 44, finally creating “green structures”; structures that need further processing to be finished. The cure station need not be a separate location, but could be built into the printers 42, 43 or otherwise provided as a means to cure the layers of material being applied. The as-printed “green” completed structures are then processed 45 to remove the supporting negative material. Additionally, structures made from metals and/or ceramics generally require a debinderizing 46 and sintering 47 process, much the same as in metal or ceramic injection molding. Polymers and ceramic and metal-filled polymers are cured depending on the requirements of the polymer system. The sacrificial material removal, debinderizing and sintering processes are dependent upon the materials and include low heat, high heat, liquid wash, evaporation, chemical dissolving, ultrasonic cleansing, isostatic pressing, heating in atmospheres of special fluids or vacuum and

other methods.

Described simply, the support bed 10 (Figure 7) or “Ziggurat” system of this invention is a folding of the proportionally long progressive wedge 2 print-forming line into the area that can be printed by a given commercial printing press. The overall size of a progressive wedge 2 print-forming line is driven by the final dimensions of the completed structure 38 being formed as well as the number of layers and their thickness. A cubic structure 38 for example, would require a long and narrow line as the horizontally sliced images of each partial structure 36 are laid out in a row, the width and number of layers driving the length of the line. The support bed 10 or “Ziggurat” system concept breaks up the length into shorter sections arranged side-by-side that would fit beneath one screen 30 (Figure 8) or other printing machine working area. For illustrative purposes, an example cubic structure is used that has thirty cross-sections or layers total, bottom to top. Even this modest number of layers requires a long progressive wedge 2. Note that only the last structure is a finished structure 38, they all advance one step at a time picking up the correct new layer with each step.

While the support bed 10 is preferably generally square with a similar number of rows and columns of steps 12 (Figure 4) for supporting the partial structures 36 thereon, the support bed 10 could be elongate as illustrated in Figure 6. In the embodiment shown in Figure 6, substrate blocks 20 are utilized upon the support bed 10 to move the partial structures 36 between adjacent steps before printing with the screen 30 and having the spaces 32 of the screen 30 printing appropriate portions of the completed structure 38. This embodiment is very similar to the progressive wedge high volume print-forming of the prior art, but includes the improvement of the substrate blocks 20, in the various embodiments identified below, to facilitate movement of the partially completed structures 36 along the support bed 10.

Another alternative which provides the support bed which is generally square can still function similarly to the progressive wedge by having multiple rows being printed

with identical spaces 32 within each column of the screen 30. Thus, multiple rows of partial structures 36 are progressing at a common rate and multiple completed structures 38 are completed after each printing process. Such a variation as is shown in Figure 9 would be particularly beneficial for relatively simple structures that do not include an excessively large number of layers to form the completed structures 38.

Most structures, however, have dimensions or numbers of layers that can utilize the benefits of the square support bed 10 or “Ziggurat,” instead of having multiple, parallel rows of identical structures being printed, perhaps over several printers, side-by-side or one long, custom printer. The square support bed 10 or “Ziggurat” fits more layers, (optimally, all the layers) of a structure under a conventional printer print area.

The support bed 10 is the mechanism under the substrate blocks 20 by which the structures 36 being built are advanced through a pattern of precise positions under the screen 30 or other printing device whereby their top surfaces 22 (Figure 10) are maintained level and on the same plane for printing purposes. The support bed 10 high volume print-forming system includes the previously described support bed 10 and substrate blocks 20 as well as shuffling and aligning systems to position and move the substrate blocks 20 along their pathway on the support bed 10. Also, while screen printing is referenced primarily in the preferred embodiment of the high volume print-forming system of this invention, this system is also applicable to other methods of printing, including offset, flexo, gravure and offset lithography, as well as other methods of applying thin layers of material to 3-D objects being built up in layers. These methods include, but are not limited to: sputtering, vapor-deposition, plating, electroforming, optical lithography, troweling, extrusion, curing with heat, light, e-beam, x-ray or the like.

With reference to Figure 10, a very simplified preferred embodiment of the support bed 10, substrate blocks 20 and shuffling system are disclosed. The support bed 10 is a rectangular mechanism that is practically the size in X and Y (length, or left to right, and width, or front-to-back, respectively) as the image area of the printer screen above it

(Figure 13). In Z (height, or top-to-bottom) direction, it preferably has a graduated, stepped top surface, the size of the rectangular steps 12 in X and Y matching that of the rectangular substrate blocks 20. The Z-axis steps 12 in the support bed 10 are small, equal to the thickness of one printed layer of a structure 38, and step progressively down across the X and Y axes from one corner to the diagonal corner in rows, left to right, then down to the next row, left to right, etc. It follows that the distance in the X and Y axis of each step 12 would be the length and width of a substrate block 20. This “stepping down” process facilitates the printing of structure layers at all the different stages of completion as represented by the images on the screen 30, all at once. The steps 12 provide a preferred form of a plurality of substrate block 20 alignment locations on the support bed 10. Other alignment locations could alternatively be provided. For instance, the support bed 10 could have a slope between alignment locations and the bottom surface 24 of the substrate blocks 20 could have a matching taper to present the surfaces 22 of the substrate blocks parallel to each other and the printer.

Preferably, contained in the thickness of the support bed 10 itself are the components that locate and control the motion of the substrate blocks 20 riding on its top, stepped surface. Therefore, every structure 36 is automatically aligned properly at every step 12 to receive its next layer from the fixed image being printed. The support bed 10 can rest upon a table 14 supporting other related equipment.

The substrate blocks 20 are small, flat, rectangular plates or substrates that the structures are printed directly upon. The substrate blocks 20 preferably include a planar top surface 22 opposite a bottom surface 24 and bordered by edges 26. These substrate blocks 20 carry the structures 36 through the print-forming process, and do not become part of the finished structures 38. They are nested tightly together in a grid-work pattern on top of the support bed 10 and located relative to one another by the support bed 10.



The substrate blocks 20 have precise locator features (in a preferred form a pair of parallel, vertical pins 25 on their bottom surface 24) that engage with a slot 16 of the support bed 10 to keep them in proper X, Y translational and rotational (theta) alignment. Specifically, and with reference to Figures 56 and 57, one precise alignment mechanism is shown. Figure 57 shows a full section view of a portion of the support bed 10 of Figure 10 if viewed from within one of the slots 16 and looking laterally at a series of three steps 12. X-Y pins 18 are shown which are adjacent a side wall of each of the slots 16. When a pin 25 extending from the bottom surface 24 of the substrate block 20 contacts both X-Y pins 18 the substrate block is precisely positioned where desired for printing. The proper rotational alignment is maintained by pushing a second pin 25 of the substrate block 20 against a theta pin 19 adjacent the side wall of the slot 16. A lateral force on the substrate block 20 or pins 25 themselves, such as applied by a spring loaded lever, toward the X-Y pins 18 and the theta pin 19 ensures contact and proper position and rotational alignment. In addition, vacuum hold-down ports can be provided with maximized surface area contact with the bottom of the substrate blocks 20 for additional traction.

The purpose of the substrate blocks 20 is to carry the structures 36 being print-formed through the entire printing process in a particular positional order on the support bed 10 as described below. As they are moved across the stepped-down surface of the support bed 10, the tops of the printed structures 36 stay co-planar and level relative to each other for printing while the substrate blocks 20 (and the bottom of the structures 36 being print-formed) step down the support bed 10. The support bed 10 forms the stair-stepped foundation, as the structures grow downward to full size, from their top surface. This can be seen in Figure 14.

Substrate block 20 movement in general: The number of different layers in a particular structure 36 is preferably the same as the number of substrate blocks 20 on the support bed 10. For the sake of this primary description, we assume that the structure

under present consideration can be print-formed with thirty print cycles, the structure 36 therefore has thirty cross-sections to be printed. The substrate block 20 flow is from left to right in the X direction, and back to front in the Y direction, with structures 36 starting in the back left position and finished structures 38 on substrate blocks 20 coming off the support bed 10 on the right front corner.

The path each substrate block 20 travels is preferably much like the path of one's eyes reading the print on a page, left to right, skip down one row, left to right, and so on. This is the order of the structure's cross-section images on the spaces 32 of the screen 30 (Figure 4) as well, and therefore each move of each substrate block 20 positions it to receive the correct next layer to build the 3-D print-formed structure 38. This movement is referred to as "shuffling" of substrate blocks 20.

Starter substrate blocks 28 (Figure 14): Every space on the support bed 10 must be filled with a substrate block 20 to receive the printed images. Because the support bed 10 has a stepped-down surface, the first set of substrate blocks 20 at the beginning of a production printing run, called "starter substrate blocks 28," are individually unique in height, each being one print-layer thicker than the previous starter substrate block 28. This assures that the top surfaces of all substrate blocks 20 are level at the start, which is usually necessary for printing.

The starter substrate blocks 28 will produce partial structures, but as they are moved through all the positions they will be replaced with the "production-run substrate blocks 20" or "regular substrate blocks 20," all of the same thickness, that carry the production-run of complete structures 38. The starter substrate blocks 28 are taller than the production-run substrate blocks 20 as they need to keep the top surface level above the stepped-down support bed 10 surface at the beginning of the printing process before there are taller printed structures consisting of multiple layers made over the declining steps of the support bed 10 (Figure 14).

Substrate block 20 movement in particular (Figure 15): The following is a description of the movement or shuffling of substrate blocks 20 at the beginning of a production print-forming run: Using the simplified example again of a structure with only thirty layers, the support bed is fully loaded with twenty-nine starter substrate blocks and one regular substrate block (in the #1 spot), and the first layer is printed on every substrate block.

The printing screen has thirty different sub-images, in the same order as the thirty substrate blocks, all acting as one large image. It will print over and over again. This printed layer prints a different image on every substrate block, only being correct (i.e., the bottom image of the structure) for the #1 substrate block in the back left corner, as every image on the screen represents a different layer of the structure, from the bottom layer up. This one substrate block represents the first production-run structure, as the rest of the substrate blocks (the starters) are just providing a surface for the screen printer to print on at the beginning of a printing run, none of the other images being the first layer of the structure, and therefore none of the starter substrate blocks carrying production-run structures.

After this first printing, all of the substrate blocks are shuffled precisely and in unison one place to the right. This leaves an empty column on the left and pushes a column of substrate blocks off the support bed on the right (Figure 16).

Displaced substrate block #30 is now finished. Being a starter substrate block with only one print on it, it is taken off-line for recycling or reclaiming by combining with "left-on-base substrate blocks" (described below). The rest of these displaced substrate blocks are then moved in the Y direction one place toward the front and reset in the X direction to the left side in the empty spaces on the support bed, both moves shown as one diagonal move. This leaves one starter substrate block with its single print displaced off the support bed altogether and one blank space in the back left corner for the addition of another new production-run substrate block (Figure 17).

As this precise, print-and-move process repeats, the starter substrate blocks all work their way through and out, each one carrying one more print on it than the last one. After twenty-nine prints, the first regular substrate block (#1) will carry the first complete structure off the support bed front right corner. From this point on, every print cycle will produce one finished structure on a continuous basis on regular production-run substrate blocks. This is where the production-run efficiency begins. Notice how the substrate block numbers have shifted for the second print from the first (Figure 18).

In this example, the printer prints all the cross-sections of one complete structure every time it prints; in thirty different places on thirty different substrate blocks, each carrying a structure that is in one unique successive stage in the process of being print-formed.

Left-on-base substrate blocks: At the end of a run there will likewise be an equal number of unfinished structures printed just to get the last needed structure through the support bed and completed. All structures that remain on the substrate blocks after that one are incomplete and may be discarded or reclaimed by combining them with the incomplete structures from the starter substrate blocks to produce complete structures. These substrate blocks at the end of a run are called “left-on-base” substrate blocks, but they are no different than production-run substrate blocks. They simply don’t have complete structures built on them and need to be cleaned off before reuse. For most production runs, the length of the run in between the starter substrate blocks and the left-on-base substrate blocks should be sufficient to make discarded quantities, if any, insignificant.

Alternatively, left-on-base substrate blocks with incomplete structures built on them may be reused, in place and as is on the support bed, as starter substrate blocks. They provide an appropriate and co-planar top surface for printing new layers of a new run, even if the structures to be printed are completely different. The new structures would simply need to have the same overall form factor to fit on the same substrate blocks on

the same support bed to use the left-on-base substrate blocks from the previous run as starter substrate blocks for the next. Thus, the left-on-base structures can be used as starters for the next run, if desired. Later these substrate blocks could be cleaned and reused.

Figure 19 shows an embodiment of a shuffling machine 50 that is used to precisely locate the support bed 10 and shuffle the substrate blocks 20 with accuracy and control on the support bed 10 between print-forming cycles. The machine 50 moves the substrate blocks 20 in the same pattern as that illustrated in Figures 15-18 described above.

Repeatable alignment is built into every component of the shuffling machine 50 (Figure 20), including the base that supports and locates a vacuum chuck to precisely hold the support bed 10, as well as provide a stable foundation for the other components, the video camera and monitor vision system 58 that provides positional feedback between print-forming cycles, the shuffling mechanism that moves the substrate blocks 20 “en bloc” one step in a controlled manner so as not to damage the partially built structures 36 on the substrate blocks 20 and the pick-and-place cartesian robot that lifts the row of substrate blocks 20 displaced from the support bed 10 and replaces them in their new position on the support bed 10.

The simplified support bed 10 shown herein is analogous to the support bed 10 shown in Figure 10. Four columns of substrate blocks 20 are shown in three rows upon the support bed 10. Because the support bed has multiple steps 12 (Figure 10) each at different heights and because the substrate blocks 20 have had different amounts of printing to form partial structures at various different stages, upper surfaces of the partial structures upon the substrate blocks are planar.

After a printing step, when shuffling is to occur, the shuffling machine 50 provides for shuffling as follows. First, the shuffler blade 52 moves toward and engages the substrate blocks 20 in the first column closest to the shuffler blade 52. The shuffler

blade 52 pushes the substrate blocks 20 a distance equal to a width of the substrate blocks 20 and into abutment with the damper blade 54 which optionally assists in preventing the substrate blocks 20 from traveling too far. The substrate blocks 20 will all drop down slightly as the steps on the support bed 10 are each one print layer thickness lower in the direction of substrate block 20 movement. The shuffler blade 52 provides one form of shuffler with other shufflers discussed below, such as the pushers 152 and 156 of Figures 58-60 and the lift rails 72 of Figures 26-31, also contemplated.

A spatula 56 or other form of lifter can then lift the entire column most distant from the shuffler blade 52 which has now moved off of the support bed 10. This last column has one substrate block 20 which includes a completed structure 38 thereon which is removed. The other substrate blocks are moved laterally to the next row and replaced at a position on the support bed 10 closest to the shuffler blade 52. Finally, a new substrate block 20 is placed in the column closest to the shuffler blade 52 and at a location in this column most distant from where the completed structure 38 was removed. The substrate blocks 20 have now been fully shuffled and are ready for another printing cycle. The above described shuffling machine 50 provides one form of a means for moving the substrate blocks 20. Other moving means are described below.

The substrate blocks 20 are moved along the substrate block 20 flow pathway as described previously and below, in Figures 21-46 and 58-60. Different methods may be used to move the substrate blocks 20 (shuffling) along the pathway and to precisely align them (registration) and lock them in place in the next position on the support bed 10 prior to print-forming the next layer. This is important to achieving the required tolerances per the design specifications of the structures 38.

Methods for shuffling the substrate blocks 20 along the substrate block flow pathway include: by hand; sliding or pushing individual substrate blocks 20 or rows of substrate blocks 20 with a mechanism from within the support bed 10, such as moving substrate blocks 20 with “rubber-wheels,” mechanical fingers, belts, magnets, vacuum,

et cetera, driven from below, sides and/or top; sliding or pushing individual substrate blocks 20 or rows of substrate blocks 20 with a mechanism from outside the support bed 10, such as shown on the shuffling mechanism 50, or in other forms such as simply mechanical, electromagnetic, hydraulic, pneumatic, electric, vacuum, et cetera.

Since all substrate blocks 20 must slide together to their new positions, it is useful to loosen them all at once from their locked registration positions and “flow” them “train-like” or “snake-like” to the new position. Note that concepts that include substrate blocks 20 traveling in a path that moves out and back into the print area are feasible. At any place where one or more adjacent substrate blocks 20 exist temporarily outside the print area, they will have an identical number of layers printed on them and will each pick up their next correct layer as they re-enter the printable area.

Methods for precisely aligning the substrate blocks 20 into the correct positions on the support bed 10 can include mating or aligning features on or between the two including: locator pins, rails, slots, wedges, walls, retainers, et cetera, which may be retractable (retracted prior to shuffling) or stationary, providing alignment from above, the sides or below, built into the support bed 10 or substrate blocks 20, or, and perhaps in addition to, shallow wells on the support bed 10 for the substrate blocks 20 to fit into. Methods for locking the substrate blocks 20 firmly onto the support bed 10 also may include: vacuum, magnetic, static electric or mechanical devices, etc. or a combination.

When the number of structure layers exceed the print screen area of a single printer screen, additional screens can be used that have the rest of the structure layer images. All the substrate blocks are printed with the first screen, then all with the second, etc., until all layers are printed, making the structure formation semi-continuous. This can be accomplished with multiple printer stations set side by side, each with it's own support bed, or with a continuous support bed that spans the multiple stations and a substrate block flow pathway that moves under the multiple printer stations (Figure 21).

There are a number of alternate substrate block 20 pathways possible, as shown in Figures 32-43 and in Figures 44 and 45, for example some being: left to right, down one row and back to the left again, left to right, down one row and back to the left again, etc. until reaching the bottom right hand corner of the support bed; variations such as right to left or bottom to top; multiple elongated S-curves or zig-zags across or up and down the support bed 10, receiving prints in both directions instead of returning to the left end in one move; circular or spiral (both around a grid of rows and columns or a true circular or irregularly curve shaped) pathway outward from the center of the support bed 10 or inward towards the center of the support bed 10; and any of the above pathways on a large support bed 10 that spans multiple printing machines. These and other similar concepts can reduce the number of independent substrate block 20 moves, making the system mechanically simpler.

If all the layers to a small structure can be spread over one half or less of the printable area of a screen, all the images can be duplicated one or more times on different places on the same screen, resulting in multiples of finished structures coming off the support bed 10 with each print cycle. Each support bed 10 in this scenario would have more than one start-to-finish path on its top, stepped surface and each substrate block 20 would only travel over one of those paths, not the whole support bed 10. A similar support bed 10 form is shown in Figure 9.

When the printed film thickness is less than one layer thickness, two or more sub-layers may be printed to create one layer. This in effect gives an improved level of detail control in that it can reduce the “layered texture” on structure side-walls, as well as being a way to provide “on-the-fly” height adjustment. If a structure is growing too quickly or not quickly enough with successive layers, a sub-layer on an entire screen print can be added or omitted. The resultant “adjustment zone” in the structure is within the minimum feature size specification and therefore not significant to the geometry of the structure but keeps it correct in the Z, or vertical dimension. Sub-layers



of positive and negative materials can be printed alternately to maintain planarity.

For the sake of simplicity in the above descriptions of the HVPF™ process, the examples are described as being print-formed with screen printing technology and there is little discussion of number of screens needed per layer beyond positive screens (for the structures themselves) and negative screens (for the temporary support material). For each layer with more than one positive material (as in multi-material structures) an additional positive screen is needed for each new material. This is analogous to standard four-color offset printing presses where there are four printing heads for the multiple colors.

After the print-forming part of the process, the structures may need to be debinderized and/or sintered. To maintain the structural integrity of pre-sintered structures through the process, the structures may remain on the substrate blocks as long as possible. Therefore the substrate blocks in this first embodiment can be constructed such that they are able to go through the removal step of the temporary “sacrificial” support material and/or possibly the sintering and debinderizing processes, along with the structures.

Planarizing and curing of the structures between print cycles are two other steps that can involve the substrate blocks. To describe the print-forming sequentially, a typical two-material print cycle, after initial substrate block alignment with vision and/or mechanical systems, may be as follows:

1. Print one layer of positive material on substrate blocks.
2. Cure the new structure layer to specific hardness in a UV light station or other curing system. Repeat steps 1 and 2 to create multiple sub-layers.
3. Print one layer of negative material around the last positive material on the same layer.
4. Cure the new negative layer to hardness in the UV light station or other curing system. This may involve more sub-layer printing.

5. Planarize the entire top layer to insure flatness of both positive and negative materials, as needed.

6. Move all the substrate blocks to new positions.

7. Repeat above.

There are applications across many disciplines and industries to which the HVPF™ process may be applied. Such uses include static and active mechanical, electromechanical, electrical, chemo and thermodynamic structures and systems. HVPF™ structures can be utilized in many practical fields such as in electromagnetic and fiber-optic devices for radio and telecommunications, pharmaceutical, medical, automotive, aerospace, computer circuits and components, et cetera. The freedom to design optimized shapes, materials and performance into such diverse applications as complex fluidics, liquid crystal displays, 3-D circuitry and mechanical components like springs, sensors or organic structural elements, requires the flexibility and adaptability of process that the HVPF™ process embodies.

With particular reference to Figure 21, a first alternative shuffling pattern is disclosed. In Figure 21 the pattern 60 provides a “back-and-forth” path depicted by the arrows which crosses multiple separate support beds 10. Figure 22 depicts use of ribbons 62 between rows of substrate blocks 20. Such ribbons can allow the substrate blocks 20 to pass freely close to each other, and such ribbons 62 could alternatively be attached to and move with the substrate blocks 20 to facilitate shuffling thereof. In contrast to previous embodiments, it is necessary with the shuffling pattern 60 for substrate blocks 20 to go from moving within a row to movement in a way which keeps the substrate blocks 20 in the same column but move to an adjacent row. When such turning is required, various different turning methodologies are disclosed in Figures 23-25.

In Figure 23 a non-rotating substrate block turning structure is shown. Particularly, a no rotation curb 64 is shown which allows the substrate blocks 20 to move to the adjacent row without rotation when abutting the no rotation curb 64.

In Figure 24 a turning system is shown which includes a rotating disk 67 and 180° rotation curbs 66. When the substrate blocks 20 are guided by the rotation curbs 66 onto the disk 67, they are rotated along this path and back onto the next row after 180° of rotation.

In Figure 25 a turning mechanism is shown which utilizes a 90° rotation curb 68 which guides the substrate blocks 20 onto an adjacent row with 90° of rotation. The amount of rotation would need to be reflected in the spaces 32 on the screen 30 for the adjacent row (Figure 4). Also, some of the substrate blocks 20 can be away from the printing area for one or more cycles, if necessary to accommodate this turning action.

With particular reference to Figures 26-31 an alternative shuffling tool 70 is described. This alternative shuffling tool 70 works with the support bed 10 and substrate blocks 20 to shift the substrate blocks 20 to the next position between printing cycles. Particularly, lift rails 72 are provided which reside within grooves 73 in the support bed 10. As depicted in Figures 26-31, the lift rails 72 can alternatively be down within the grooves 73 or lift up out of the grooves 73 to lift the substrate blocks 20 off of the support bed 10. The substrate blocks 20 can then be moved laterally and the lift rails 72 can be returned down into the grooves 73 with the substrate blocks 20 having been moved.

With particular reference to Figures 32-43 a second alternative shuffling pattern is described. In this pattern, a spiral shuffling pattern is followed. Particularly, a finished block 82 is removed from a center of the support bed 10. A first moving block 83 would then be shifted to where the finished block 82 previously resided before it was removed. Next, a second moving block 84 would be shifted to the vacated space. The vacated space in Figures 32-43 are depicted with stippling. Spaces with dots therein represent substrate blocks 20 which have completed their movement.

Next, a third moving block pair 85 (Figure 35) would be shifted together linearly. Next, a fourth moving block pair 86 (Figure 36) would be shifted as shown. Next, a fifth

moving block triplet 87 would be moved linearly as depicted in Figure 37. Next a sixth moving block triplet 88 would be moved linearly as depicted in Figure 38.

This system would be continued as indicated until the last moving block row 89 is moved linearly as depicted in Figure 43. Hence, twelve steps would be involved to shift all thirty-six substrate blocks to their new position before the next printing step. This shuffling pattern could also be operated in a pattern reverse to that described above.

Figures 44-46 depict further various alternative shuffling patterns. In Figure 44 a third alternative shuffling pattern is disclosed which is a generally spiraling pattern spaced upon three substrate support beds 10. Figure 45 provides a fourth alternative shuffling pattern 92 which is a generally zig-zag pattern split onto three separate support beds 10. Such variations in the shuffling pattern could also be applied to an embodiment using a single support bed 10, which is generally preferred when practiced.

Figure 46 shows a fifth alternative shuffling pattern 94 which is a generally zig-zag pattern spaced across three separate support beds and with multiple steps spaced on the support beds being provided at a common height should the high volume print-forming method being utilized call for such an arrangement. This pattern 94 could also be employed on a single support bed 10.

With particular reference to Figures 47-55, details of the substrate block holding and alignment systems are described. Most preferably, vacuum systems are utilized to securely hold the substrate blocks 20 upon the support bed 10 when printing. In Figure 47, a substrate block holding tool 100 is shown integrated into the support bed 10. Each of the steps 12 includes at least one vacuum hole 104. A registration wall 102 is preferably provided along one side of the support bed 10. A manifold 105 is coupled to each of the vacuum hole 104 and to a vacuum supply port 106. An end wall 108 is also provided opposite the registration wall 102. The end wall 108 can provide a force upon substrate blocks securing them up against the registration wall 102 to ensure proper position. The end wall 108 and registration wall 102 would thus function somewhat like

a vise as well as for proper alignment.

Vacuum would then be applied to secure the substrate blocks down against the steps 12 of the support bed 10. Printing could then occur. Most preferably, rather than merely providing vacuum holes 104, a vacuum groove 116 would be provided on each of the steps 112. Additionally, support holes 114 and support slots 115 could be provided through which lift pins 117 could pass. The lift pins 117 would be coupled to a separate pin support plate 118 capable of moving up and down through the support holes 114 and slots 115 to pass into registration holes 120 and registration slots 121 provided in the substrate blocks 20. These lift pins 117 could provide the dual function of properly aligning the substrate blocks 20 upon the support bed 10 and lifting the substrate blocks 20 slightly up off of the support bed 10 to break the vacuum seal that may tend to form, so that the substrate blocks 20 are ready for shuffling.

While a spiral pattern for the vacuum groove 116 is shown in Figure 48, and similarly in Figure 51, other patterns could similarly be provided. For instance, a multiple hole pattern 122 could be provided (Figure 50). A spiral pattern 124 could be provided (Figure 51). A multiple cavity pattern 126 could be provided (Figure 52) or a star pattern 128 could be provided (Figure 53).

As an alternative (or in addition) to utilization of vacuum to hold the substrate blocks 20 in position upon the support bed 10, a magnetic holding tool 130 could be utilized (Figure 54). With such a system, magnetic force would be applied, such as through actuation of a lever 132 to bring magnets into proper position to secure the substrate blocks 20 to the steps 12 of the support bed 10.

As another alternative, a mechanical holding tool 140 could be utilized which uses mechanical force to hold the substrate blocks 20 adjacent the support bed 10. In particular, substrate blocks 20 could be rotated against a stop 142 for proper positioning and then rods 144 could be rotated to turn clamps 146 into position to engage the substrate blocks 20 and secure them down upon the support bed underlying the

substrate blocks 20. With either vacuum, magnetic or mechanical holding tools, the substrate blocks 20 are held securely in place during the printing process to ensure that the next successive layers for the structure are properly placed in the precise position required for the proper formation of the structures.

With particular reference to Figures 58-60, a second alternative shuffling tool 150 is described for facilitating shuffling according to the shuffling pattern 60 of Figure 21, shown on a single support bed 10 of twenty numbered substrate blocks 20 for illustration purposes. This tool includes a left pusher 152 with multiple fingers 154 and a right pusher 156 with multiple fingers 158. The pushers 152, 156 have their fingers 154, 158 abutting the opposite ends of alternating rows of substrate blocks 20. The pushers 152, 156 first move toward each other to offset alternating rows by two substrate blocks (Figure 59). Next, the pushers 152, 156 move laterally to relocate substrate blocks 20 at the ends of rows down to the next row (Figure 60). Finally, the pushers 152, 156 push the substrate blocks 20 of each row back together with each block 20 having advanced one space. With each cycle a last block 20 is removed (#20) and anew block 20 is added (#0).

This disclosure is provided to reveal a preferred embodiment of the invention and a best mode for practicing the invention. Having thus described the invention in this way, it should be apparent that various different modifications can be made to the preferred embodiment without departing from the scope and spirit of this disclosure. When structures are identified as a means to perform a function, the identification is intended to include all structures which can perform the function specified.